LENSED FIBER FOR OPTICAL INTERCONNECTIONS

Cross-Reference to Related Applications

[0001] This application is a continuation-in-part of U.S. Patent Application Serial No. 10/319,748, entitled "Lensed Fiber for Optical Interconnections," filed December 13, 2002. This applications claims priority to U.S. Provisional Application 60/486,087, entitled "Lensed Fiber for Optical Interconnections," filed July 9, 2003.

Background of Invention

[0002] The invention relates generally to optical interconnections. More specifically, the invention relates to a lensed fiber capable of refracting light coming into and out of an optical fiber into a collimated or focused beam and to a method of making the lensed fiber.

[0003] A lensed fiber is a monolithic device having an optical fiber that is terminated with a lens. Lensed fibers are advantageous because they do not require active alignment and bonding of the optical fiber to the lens, they have low insertion loss, and they enable component miniaturization and design flexibility. Lensed fibers are easily arrayed and are therefore desirable for making arrayed devices such as variable optical attenuators and optical isolators, for use in silicon optical bench applications, for use as high power connectors and dissimilar fiber connectors, and for coupling optical signals into other micro-optic devices. In addition, the spot size and working distance of a lensed fiber can be tailored for a specific application. For example, the spot size and working distance of a lensed fiber can be tailored to produce the smaller beam diameters that can allow use of smaller micro-electro-mechanical systems (MEMS) mirrors in optical switches.

[0004] Figure 1A shows a prior-art lensed fiber **100** having a lens **102** spliced to an optical fiber **104**. The lens **102** has a convex region **106** that refracts light coming out of the optical fiber **104** into a collimated or focused beam. The lens **102** has a neck region **108** that connects the convex region **106** to the optical fiber **104**. The diameter of the neck region **108** is larger than the outer diameter of the optical fiber **104**, resulting in the overall diameter of the lensed fiber **100** being greater than the outer diameter of the optical fiber **104**. Hence, the lensed fiber **100** would not be able to fit into a standard glass or ceramic ferrule or groove, such as an etched groove on a silicon chip, designed to hold the optical fiber **104**. Instead, a

specialized ferrule or groove would have to be designed to hold the lensed fiber **100**. As can be appreciated, the lens **102** can have a wide range of geometries, and designing a specialized ferrule or groove to hold each lens geometry would be difficult and not cost-effective.

[0005] Figure 1B shows a prior-art lensed fiber **110** having a lens **114** spliced to an optical fiber **112**. The lens **114** has convex region **118** that refracts light coming out of the optical fiber **112** into a collimated or focused beam. The lens **114** has a neck region **116** having a diameter that is equivalent to the outer diameter of the optical fiber **112**. If the radius of curvature (Rc) of the convex region **118** is greater than half of the outer diameter of the optical fiber **112**, the overall diameter of the lens **114** would be greater than the outer diameter of the optical fiber **112**, resulting in the overall diameter of the lensed fiber **110** being larger than the outer diameter of the optical fiber **112**. In this case, the lensed fiber **110** would not fit into a standard glass or ceramic ferrule or groove, such as an etched groove on a silicon chip, designed to hold the optical fiber **112**. Instead, as previously discussed, a specialized ferrule or groove would have to be designed to hold the lensed fiber **110**.

[0006] Theoretically, it would be expected that if the radius of curvature of the convex region **118** is less than or equal to half the outer diameter of the optical fiber **112** and the diameter of the neck region **116** is equivalent to the outer diameter of the optical fiber **112**, then the overall diameter of the lens **114** would not exceed the outer diameter of the optical fiber **112**. However, in practice, this is usually not the case. The process used in forming the radius of curvature at the tip of the lens often results in the lens having a match-stick shape and an overall diameter that is larger than the outer diameter of the optical fiber. Figure 1C shows a lensed fiber **120** having a lens **122** with a match-stick shape. The match-stick shape results in the overall diameter of the lensed fiber **120** being slightly larger than the outer diameter of the optical fiber **124**, even though the radius of curvature of the convex region **126** of the lens **120** is smaller than half the outer diameter of the optical fiber **124**.

[0007] Typically, a bulge is also formed at the splice junction between the lens and optical fiber which can increase the overall diameter of the lensed fiber. For example, Figure 1C shows a bulge **128** formed at the splice **130** between the lens **122** and the optical fiber **124** as a consequence of the splicing process. The bulge **128** results in the overall diameter of the lensed fiber **120** being slightly larger than the outer diameter of the optical fiber **124**, even though the diameter of the neck region **132** of the lens is equivalent to the outer diameter of

the optical fiber **124**. Because of the bulge **128** at the splice **130** and the match-stick shape of the lens **122**, the lensed fiber **120** may not be able to fit into a standard glass or ceramic ferrule or in a groove, such as an etched groove on a silicon chip, designed to hold the optical fiber **124**. In addition, the bulge **128** makes it difficult to maintain straight alignment of the lensed fiber **120** in a groove, such as an etched groove on a silicon chip.

[0008] From the foregoing, there is desired a lensed fiber that is capable of refracting light coming into and out of an optical fiber into a collimated or focused beam and that can be cost-effectively packaged in a standard design ferrule or groove configuration.

Summary of Invention

[0009] In one aspect, the invention relates to a lensed fiber which comprises an optical fiber and a lens having a neck region and a convex region formed at an end of the optical fiber. The neck region has an overall diameter that is smaller than an outer diameter of the optical fiber.

[0010] In another aspect, the invention relates to a method of making a lensed fiber which comprises splicing a coreless fiber to an optical fiber. The coreless fiber has a diameter smaller than an outer diameter of the optical fiber. The method further includes controllably applying heat and axial tension to the coreless fiber to form a lens having a neck region and a convex region. The neck region has an overall diameter that is smaller than the outer diameter of the optical fiber.

[0011] In another aspect, the invention relates to a method of making a lensed fiber which comprises splicing a coreless fiber to an optical fiber, cleaving the coreless fiber to a desired length, and melting back the cleaved end of the coreless fiber to form a lens having a radius of curvature at its tip and an overall diameter that does not exceed the outer diameter of the optical fiber. The coreless fiber has a diameter that is smaller than an outer diameter of the optical fiber.

[0012] In another aspect, the invention relates to a method of making a lensed fiber which comprises splicing a coreless fiber to an optical fiber, wherein the coreless fiber has a diameter that is equal to or larger than an outer diameter of the optical fiber. The method further includes controllably applying heat and axial tension to the coreless fiber until the diameter of the coreless fiber becomes smaller than the outer diameter of the optical fiber and

taper-cutting the coreless fiber to form a lens having a neck region and a convex region. The neck region has a diameter that is smaller than the outer diameter of the optical fiber.

[0013] Other features and advantages of the invention will be apparent from the following description and the appended claims.

Brief Description of Drawings

[0014] Figure 1A shows a prior-art lensed fiber having a lens with a neck region that is larger in diameter than the optical fiber to which the lens is attached.

[0015] Figure 1B shows a prior-art lensed fiber having a lens with a neck region that is equivalent in diameter to the optical fiber to which the lens is attached.

[0016] Figure 1C shows a prior-art lensed fiber having a lens with a match-stick shape.

[0017] Figure 2 shows a lensed fiber having a lens with a neck region that is smaller in diameter than the optical fiber to which the lens is attached according to one embodiment of the invention.

[0018] Figure 3A illustrates an alignment step of a method of making a lensed fiber according to one embodiment of the invention.

[0019] Figure 3B illustrates a fusion-splicing step of a method of making a lensed fiber according to one embodiment of the invention.

[0020] Figure 3C illustrates a taper-cutting step of a method of making a lensed fiber according to one embodiment of the invention.

[0021] Figure 3D shows the lensed fiber after the taper-cutting step illustrated in Figure 3C.

[0022] Figure 3E illustrates a melt-back step of a method of making a lensed fiber according to one embodiment of the invention.

[0023] Figure 4A shows mode field diameter as a function of lens thickness and radius of curvature for a single-mode fiber at 1550 nm for an embodiment of the invention.

[0024] Figure 4B shows distance to beam waist as a function of lens thickness and radius of curvature for a single-mode fiber at 1550 nm for an embodiment of the invention.

[0025] Figure 4C shows the nomenclature used for the lens geometries shown in Figures 4A and 4B.

[0026] Figure 5A shows a coreless fiber having a cleaved end fusion-spliced to an optical fiber.

[0027] Figure 5B shows the cleaved end of the coreless fiber of Figure 5A rounded into a desired radius of curvature according to another embodiment of the invention.

[0028] Figure 6 shows a lensed fiber having a lens formed from a coreless fiber that initially has a diameter that is larger than the outer diameter of the optical fiber to which the lens is attached.

[0029] Figure 7 shows a lensed fiber having a lens with a tapered neck region according to another embodiment of the invention.

Detailed Description of Preferred Embodiments

[0030] The invention will now be described in detail with reference to a few preferred embodiments, as illustrated in accompanying drawings. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that the invention may be practiced without some or all of these specific details. In other instances, well-known features and/or process steps have not been described in detail in order to not unnecessarily obscure the invention. The features and advantages of the invention may be better understood with reference to the drawings and discussions that follow.

[0031] Embodiments of the invention provide a lensed fiber having a lens disposed at an end of an optical fiber. The lens has a convex region and a neck region, and the neck region has an overall diameter that is smaller than the outer diameter of the optical fiber. In some embodiments, the neck region is straight. In other embodiments, the neck region is tapered. By making the overall diameter of the neck region smaller than the outer diameter of the optical fiber, the convex region of the lens can be made with a wide range of

prescriptions without the overall diameter of the lens exceeding the outer diameter of the optical fiber. As a result, the lensed fiber can be packaged in standard glass or ceramic ferrules or grooves, such as grooves etched on silicon chips, or other receptacles designed to hold the optical fiber.

[0032] Figure 2 shows a lensed fiber **200** according to an embodiment of the invention. The lensed fiber **200** includes a planoconvex lens **202** disposed at an end of an optical fiber **204**. The lens **202** may be attached to the optical fiber **204** by a fusion splicing process or other suitable attachment process, e.g., by an index-matched epoxy. In general, fusion splicing would produce a more robust connection between the lens **202** and the optical fiber **204**. In one embodiment, the optical fiber **204** is a stripped region of a coated optical fiber (or pigtail) **206**. The optical fiber **204** has a core **208** and a cladding **210** surrounding the core **208**. The optical fiber **204** could be any single-mode fiber, including polarization-maintaining (PM) fiber, or a multimode fiber. In operation, a light beam **212** traveling down the core **208** diverges upon entering the lens **202** and is refracted into a collimated or focused beam upon exiting the lens **202**. Whether the beam emerging from the lens **202** is collimated or focused depends on the ratio of the thickness of the lens to the radius of curvature of the lens.

[0033] The lens **202** has a neck region **214** and a convex region **216**. The lens **202** is made from a coreless fiber having a diameter that is smaller than the outer diameter of the optical fiber **204**, resulting in the neck region **214** having a diameter that is smaller than the outer diameter of the optical fiber **204**. The cross-section of the neck region is typically circular but could also have other shapes, e.g., rectangular. Therefore, the term "diameter" of the neck region is intended to refer to a dimension, usually the largest dimension, at a cross-section of the neck region. A lens having a neck region with a diameter that is smaller than the outer diameter of the optical fiber to which it is attached provides packaging and manufacturing advantages compared to a lens having a neck region with a diameter that is the same as or larger than the outer diameter of the optical fiber to which it is attached.

[0034] Typically, the coreless fiber used in making the lens **202** is made of silica or doped silica, e.g., B_2O_3-SiO_2 and GeO_2-SiO_2, and has a refractive index similar to the refractive index of the core **208** of the optical fiber **204**. The coefficient of thermal expansion of the lens **202** can be matched to that of the optical fiber **204** to achieve better performance

over a desired temperature range. The lens **202** may be coated with an anti-reflection coating to further reduce back-reflection loss. A back-reflection loss lower than -55 dB is generally desirable.

[0035] A method of making a lensed fiber, such as described in Figure 2, will now be described with reference to Figures 3A-3D. In Figure 3A, the method starts with aligning the axial axis of an optical fiber **300** to the axial axis of a coreless fiber **302**. In this method, the coreless fiber **302** will be attached to the optical fiber **300** and shaped into a planoconvex lens having a neck region and a convex region. In order to allow the diameter of the neck region to be smaller than the outer diameter of the optical fiber **300**, the diameter of the coreless fiber **302** is selected to be smaller than the diameter of the optical fiber **300**. After aligning the axial axes of the optical fiber **302** and the coreless fiber **302**, the opposing ends of the optical fiber **300** and coreless fiber **302** are brought together, as shown in Figure 3B, and are spliced together using a heat source **304**. The heat source **304** may be a resistive filament or other suitable heat source, such as an electric arc or laser.

[0036] After splicing the coreless fiber **302** to the optical fiber **300**, the coreless fiber **302** is taper-cut to a desired length. As shown in Figure 3C, taper-cutting involves positioning a heat source **306** at a desired location along the coreless fiber **302**. The position of the heat source **306** along the coreless fiber **302** determines the thickness of the lens. The heat source **306** is then operated to deliver a controlled amount of heat to the coreless fiber **302** while pulling the coreless fiber **302** in the direction indicated by the arrow. The heating and pulling actions cut the coreless fiber **302** to a desired length. Further, as shown in Figure 3D, a convex surface **308** having a desired radius of curvature is formed at the distal end of the coreless fiber **302**. When a resistive filament is used as the heat source (**306** in Figure 3C) the heat distribution along the circumference of the coreless fiber **302** is very uniform, allowing for the formation of a spherical convex surface with a symmetrical mode field.

[0037] The radius of curvature of the convex surface **308** depends on the power output of the heat source (**306** in Figure 3C). Typical power used for taper-cutting the coreless fiber **302** using a resistive filament is in a range from 22 to 30 W, depending on the desired radius of curvature. The radius of curvature of the convex surface **308** can also be affected by the duration of heating. In general, the longer the heating time after the coreless fiber **302** is severed, the larger the radius of curvature. The radius of curvature that can be

achieved with the taper-cutting process alone is small, typically between 5 μm and 60 μm. However, this radius of curvature can be enlarged by a melt-back process. As shown in Figure 3E, the melt-back process involves placing the heat source **306** in front of the convex surface **308** and moving the heat source **306** towards the convex surface **308**. The convex surface **308** is melted back by the heat to form a larger radius of curvature, as indicated by the dotted lines **310**. The heat applied to the convex surface **308** and the duration of the heating are controlled to obtain the desired radius of curvature.

[0038] By using taper-cutting and melting-back processes for the lensed fiber formation, it is possible to make a lens with a radius of curvature (Rc) that is less than or equal to half of the outer diameter of the optical fiber without the diameter of the lens exceeding the diameter of the optical fiber. The maximum lens thickness is determined by clipping of the beam at the apex of the lens:

$$T_{max} = \frac{D}{\pi \cdot \tan\left(\dfrac{\lambda}{\pi \cdot w_o}\right)} \qquad (1)$$

where D is 2xRc, λ is wavelength in the lens material, and w_o is the mode field radius of the optical fiber at the splice to the lens. To produce a diffraction-limited beam, i.e., a beam with a single peak, the radius of curvature at the tip of the lens should not be smaller than the mode field radius of the optical fiber at the splice to the lens.

[0039] Figures 4A and 4B show examples of lens geometries that can be made with a single mode fiber, such as Corning SMF-28® optical fiber, having an outer diameter of 125 μm. Figure 4A shows a plot of mode field diameter at beam waist (MFDW in Figure 4C) at 1550 nm as a function of lens thickness and radius of curvature (Rc) of the convex surface at the tip of the lens. Figure 4B shows a plot of distance to beam waist (DW in Figure 4C) at 1550 nm as a function of lens thickness and Rc of the convex surface at the tip of the lens. For a single mode fiber having an outer diameter of 125 μm, the lens can be made to have a maximum possible Rc of 62.5 μm without the overall diameter of the lens exceeding the outer diameter of the optical fiber. In these examples, the maximum thickness of the lens if made from silica and operating at free space wavelength of 1550 nm (D = 125 μm, w_o = 6 μm) is 697 μm.

[0040] For a lensed fiber made by taper-cutting and melting-back, if Rc of the lens is greater than half of the OD of the optical fiber, the overall diameter of the lens will be greater than the outer diameter of the optical fiber. In this case, making the lens from a coreless fiber with a diameter that is smaller than the outer diameter of the optical fiber still has packaging and manufacturing advantages compared to making the lens from a coreless fiber with a diameter that is equal to or larger than the outer diameter of the optical fiber. With a coreless fiber having a diameter equivalent to the outer diameter of the optical fiber, a bulge is created on the splice between the optical fiber and the coreless fiber, as previously discussed. With a coreless fiber having a diameter larger than the outer diameter of the optical fiber, the amount of energy required to cut the coreless fiber is larger. By using a smaller-diameter coreless fiber, it is possible to reduce the power output required to form the lens. Because of the smaller volume of the glass, the heat transfer is more uniform than with a larger-diameter coreless fiber, so the effects of asymmetry of heat source has lesser impact. The centering of the curvature of the lens with respect to the core of the optical fiber is also accomplished more successfully using a smaller volume of glass.

[0041] Figure 5A shows a lensed fiber **500** according to another embodiment of the invention. The lensed fiber **500** includes a lens **502** that is attached to an optical fiber **504**. The lens **502** has a convex surface **506**. The lensed fiber **500** is formed by fusion-splicing a coreless fiber (**508** in Figure 5B) to the optical fiber **504** and cleaving the coreless fiber to a desired length by, for example, a mechanical or laser cleaver. The cleaved end (**510** in Figure 5B) essentially has an infinite radius of curvature. A melt-back process, such as described above, can then be used to form any radius of curvature (Rc) at the cleaved end. Unlike the method described above which starts the melt-back with a smaller Rc than the final lens Rc, this method starts melt-back with an infinite Rc that is decreased by the heating process. Thus, this method does not require the convex surface **506** to be a full sphere. In this case, a convex surface with Rc greater than half of the outer diameter of the optical fiber **504** can be made without the overall diameter of the lens exceeding the outer diameter of the optical fiber **504**.

[0042] Figure 6 shows a lensed fiber **600** according to another embodiment of the invention. The lensed fiber **600** includes a lens **602** disposed at an end of an optical fiber **604**. In this embodiment, the lens is formed from a coreless fiber having a diameter that is larger than or equal to the diameter of the optical fiber **604**. The lensed fiber is formed by

aligning and fusion-splicing the coreless fiber to the optical fiber **604**. The coreless fiber is then pulled in a direction away from the optical fiber such that the resultant neck region **606** of the lens **602** would exhibit a diameter that is smaller than the diameter of the optical fiber **604**. This pulling action also eliminates any bulge at the splice **608** between the optical fiber **604** and the coreless fiber. The coreless fiber is then taper-cut at a desired location to form the convex surface **610**. A melt-back process may be used to enlarge the radius of curvature of the convex surface **610**, as previously described.

[0043] For the lensed fiber **600**, the radius of curvature of the convex surface **610** that can be formed without the overall diameter of the lens **602** exceeding the outer diameter of the optical fiber **604** is relatively small. For example, for an optical fiber having an OD of 125 μm, the overall diameter of the lens **602** starts to exceed the overall diameter of the optical fiber **604** when the Rc of the lens **602** is greater than about 53 μm. For an optical fiber having an OD of 125 μm, the thickness of the lens **602** is also limited to about 250 μm. Above this limit, the overall diameter of the lens **602** starts to exceed the overall diameter of the optical fiber **604**.

[0044] Figure 7 shows a lensed fiber **700** according to another embodiment of the invention. The lensed fiber **700** includes a lens **702** disposed at an end of an optical fiber **704**. The lens **702** has a neck region **706** and a convex region **708**. In this embodiment, the neck region **706** is tapered. In one embodiment, the lens **702** is formed from a coreless fiber that is smaller in diameter than the optical fiber **704**. The coreless fiber is aligned to the optical fiber, and a splice is formed between the coreless fiber and the optical fiber **704** using a fusion process. The coreless fiber is then stretched in a direction away from the optical fiber **704** while heat is applied along the coreless fiber, including the splice region. The heat may be applied using a resistive filament or other suitable heat source. The heating and stretching actions taper the coreless fiber and smoothen the splice region, as shown at **710**. The heating and stretching actions may include cutting the coreless fiber to a desired length. Heat is applied to the distal end of the coreless fiber, i.e., the end farthest from the optical fiber **704**, to allow surface tension to pull the distal end of the coreless fiber into a convex surface, as shown at **708**.

[0045] For illustration purposes, Table 1 shows calculated properties of lensed fibers similar to the one shown in Figure 7. For lensed fiber A, a coreless fiber having a diameter of

100 μm was spliced to an optical fiber having an outer diameter of 125 μm. For lensed fiber B, a coreless fiber having a diameter of 200 μm was spliced to an optical fiber having an outer diameter of 125 μm. Lenses were formed at the end of the coreless fibers using the processes previously described. Lensed fibers having a pointing error less than 0.5 μm (or pointing angle less than 0.5°) were selected. The radius of curvature of the lenses was approximately 62 μm, and the thickness of the lenses was approximately 285 μm. The lens properties shown in Table 1 are calculated assuming free-space wavelength of 1550 nm. The low back-reflection loss is achieved without use of AR coating. With AR coating, back-reflection loss of -55 dB or lower may be achieved.

Table 1

Lensed Fiber	Mode Field Diameter (μm)	Distance to Beam Waist (μm)	Back-reflection Loss (no AR, dB)
A	13 ± 1.5	260 ± 10	-43
B	16 ± 1.5	260 ± 10	-40

[0046] The invention provides one or more advantages. A lensed fiber such as disclosed herein with a lens having an overall diameter that is the same as or smaller than the diameter of the optical fiber can be easily packaged into a standard glass or ceramic fiber ferrule. The lens can be inserted directly into the ferrule without having to thread the pigtail through the ferrule. The lens can also be easily arrayed or placed into a standard multi-fiber ferrule. The lens can also be easily packaged into V-grooves or other etched structures on silicon chips or other semiconductor platforms. The invention provides an ideal lens for small optical MEMS switches, VOAs, and silicon optical bench applications.

[0047] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.